Bus Differential Protection

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Introduction

A variety of methods have been used to implement bus differential relaying schemes. The introduction of digital technology has led to further improvements in bus differential protection. It is the purpose of this paper to review the various methods that have been used and to discuss improvements that can be provided via digital technology.

Basic Conditions

Khirchoff's current law states that the sum of the currents entering a given node must be equal to the currents leaving that node. Consider the two situations demonstrated for the simple bus shown in Figure 1.

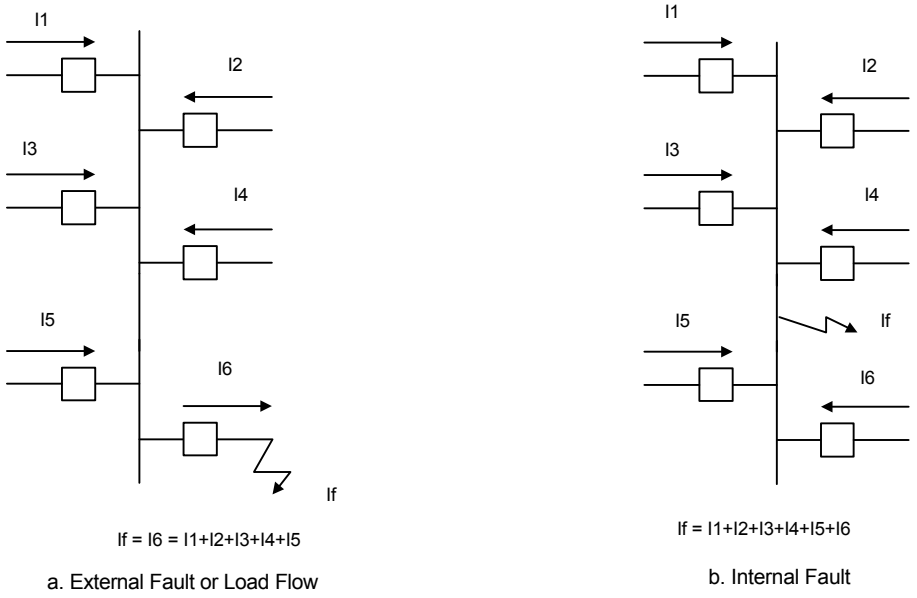


Figure 1 - Simple Bus Arrangement

For the case of an external fault, the current leaving the bus is equal to the sum of all of the currents entering the bus, and the total summation is zero. The same would be true when considering load flow. On the other hand, for the case of an internal fault, the sum of all of the currents entering the bus is equal to the total fault current (summation is not zero). An ideal

differential relaying system takes advantage of the fact that the sum of the currents will be zero for external faults or load flow, whereas the sum will be equal to the total fault current for internal faults. Unfortunately, there are problems introduced wherein the ideal cannot always be obtained, and steps must be taken to insure that the differential relaying system works properly, even under non-ideal conditions.

Basic Differential System

A basic differential relaying system is shown in Figure 2. The current transformers (CT's) are all connected with the same ratio and polarity sense so that the currents circulate amongst the CT's (Id = 0) for all external faults and load flow whereas the total fault current (Id = If) will flow through the relay (R) for all internal faults.

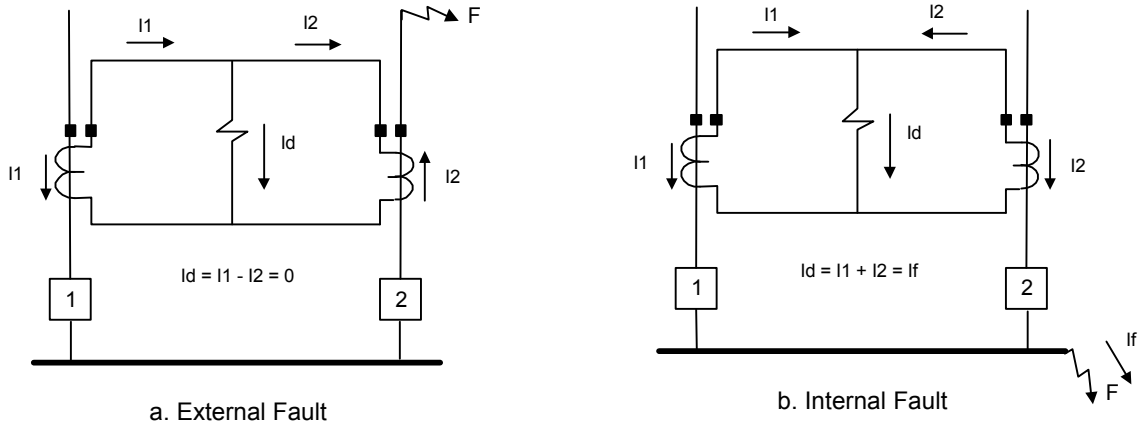


Figure 2 - Basic Differential System

If the CT's behaved ideally, the differential system shown in Figure 2 would be very easy to implement using a simple overcurrent type of relay. Unfortunately, the CT's may saturate and thus may cause the differential system to operate in other than an ideal way.

CT Saturation

CT saturation occurs when the flux required to produce the secondary current exceeds the saturation flux density of the core as dictated by the physical dimensions of the CT. Whether or not any given current transformer will saturate is dependent on the following factors:

- CT ratio
- Core cross-sectional area
- Connected burden
- Magnitude of burden
- Presence and amount of remanent flux (if any)
- Amount and direction of dc offset in the current (if any)
- Saturation flux density of the core steel

A typical case of CT saturation is shown in Figure 3 for a fully offset current wave having a time constant of approximately 30 milliseconds. The time to saturation (the point where the secondary current starts to distort) is dependent on the factors listed above, and can be determined as described in reference 1.

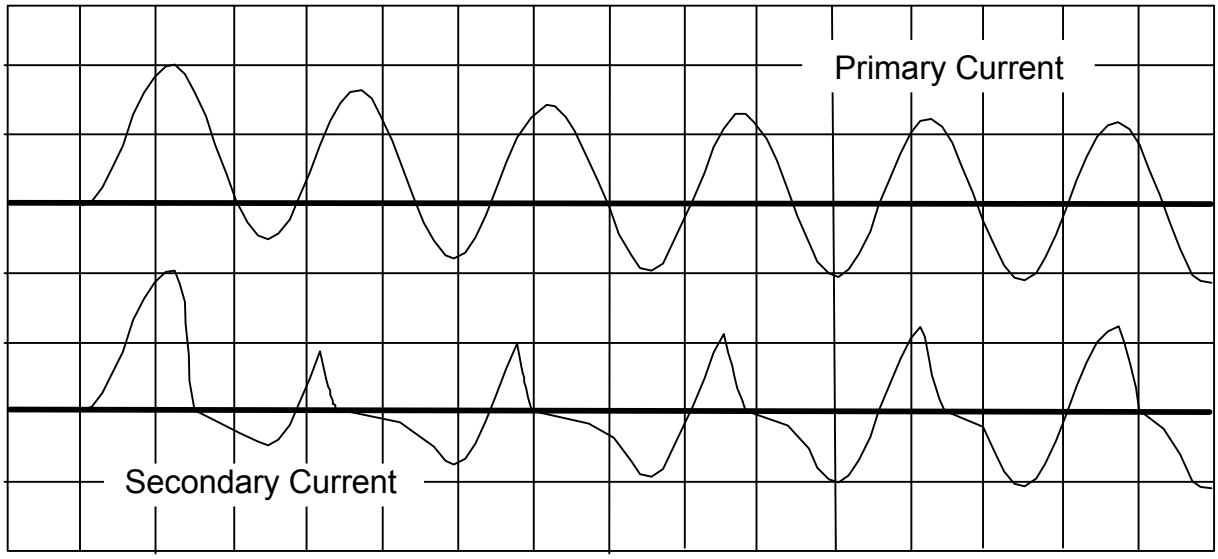


Figure 3 - Effects of CT Saturation

The important thing to note is that the secondary current can be quite distorted relative to the primary current. In this example, the secondary current is quite distorted for at least five cycles. If conditions are severe enough, it is possible that the distortion may be even worse than shown in the example, and that saturation can start to occur even sooner. The CT will eventually come out of saturation and the secondary current will then have the same shape as the primary. How long this takes is also dependent on the factors given earlier. It is the distortion in the secondary current that can cause problems in the bus differential circuit and quite possible in other relaying circuits.

A simplified circuit for a current transformer is shown in Figure 4.

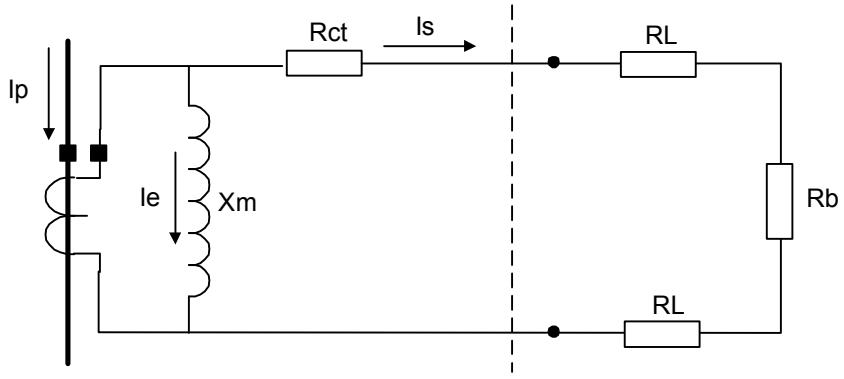
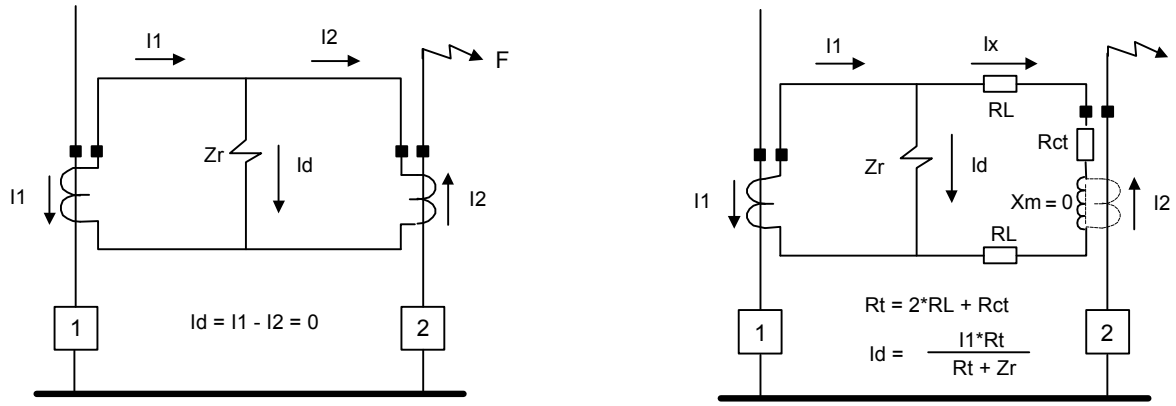


Figure 4 - Simplified CT Circuit with Connected Burden

This circuit is typically representative of a bushing type current transformer that is wound with fully distributed windings on a toroidal core. It is generally accepted that the leakage reactance in this type of CT is negligible and therefore can be represented as shown (with resistive component only). When the CT saturates, the magnetizing impedance is assumed to go to zero and the secondary current also goes to zero at that time. The effect on relay performance will depend on the type of relay that is being used. Only the effect on bus differential relaying will be discussed in this paper.

Overcurrent Relay

The differential circuit using a simple overcurrent relay is shown in Figure 5. An external fault is illustrated.



a. Without CT Saturation

b. With CT Saturation

Figure 5 - Differential Circuit Using a Simple Overcurrent Relay

If there is no saturation, the differential current (Id) will be zero and there will be no tendency for the relay to operate. If there is saturation, Id will not equal zero and a simple overcurrent relay would operate if Id exceeded the setting of the function. If complete saturation is assumed (not likely), then Id could be calculated as shown in Figure 5b. This represents the worst case situation. The overcurrent relay could then be set above this value to prevent operation due to CT saturation. This could require very high settings that may not be sensitive enough to detect the minimum possible bus fault. Another way to overcome the problem would be to introduce time delay to the overcurrent function, but it is difficult to determine exactly how much time is required to prevent operation. Even if the time could be determined accurately, it may be too long from a system point of view, and it could lead to stability problems.

High Impedance (voltage operated) Differential Relay

The application of a high impedance differential relay is shown in Figure 6. This relay is applied on the assumption that the CT associated with the faulted feeder (carries the total fault current) saturates completely. For that condition, the CT can be represented by a simple resistive component (toroidal CT). The relay, which is connected across the junction point of the CT's has

an impedance which is much greater than the total resistance of the CT circuit which is comprised of the CT resistance plus any lead resistance from the junction point to the relay. The voltage (Vr) produced across the relay will then be equal to the drop in the resistance resulting from the total fault current flowing through this resistance. Calculations are made for each CT circuit to determine the maximum possible voltage that can be developed across the relay (assuming total saturation in each circuit). The relay is then set greater than this voltage by a suitable margin.

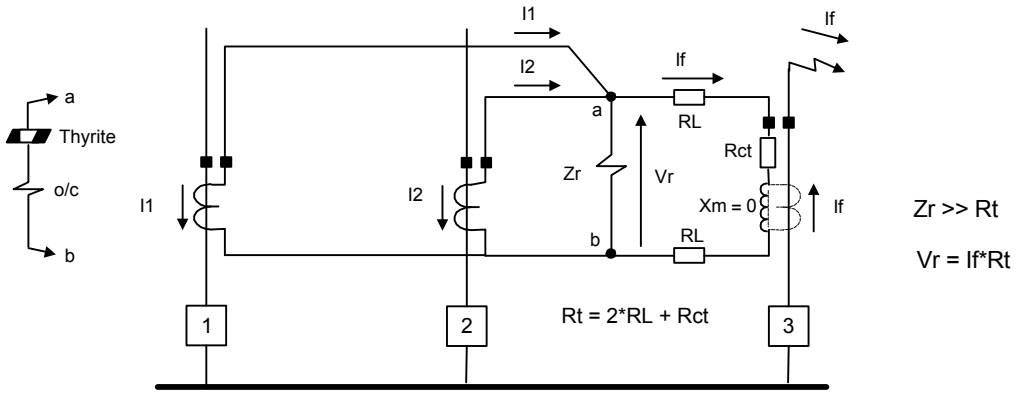


Figure 6 - High Impedance (voltage operated) Differential Relay

The assumption that the CT appears to be purely resistive when totally saturated is based on the CT being of toroidal construction with completely distributed windings. For this type of CT, the leakage reactance will be negligible and the above assumption is valid. The relay can be applied with other than toroidal CT's but the leakage reactance must be known in order to determine a setting for the relay. If the reactance is too large, it may not be possible to use the relay because too high a setting may result.

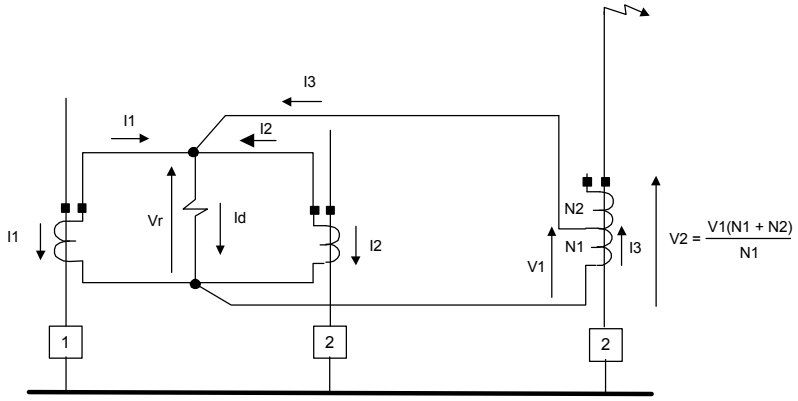


Figure 7 - Ratio Matching with Multi-ratio CT's

For internal faults, extremely large voltages will try to be developed across the relay because of the high impedance. This could lead to damage to the CT's and/or relay if precautions are not taken to limit the voltage to reasonable levels. The Thyrite circuit shown in Figure 6 is one

technique that is used for voltage limiting. The Thyrite, which exhibits an inverse resistance characteristic with increasing voltage, is connected directly across the relay. By proper selection of the Thyrite, reasonable voltage levels can be established. For very heavy faults, the Thyrite will carry a significant amount of current, thus, a simple overcurrent (o/c) relay is placed in series with the Thyrite to provide additional protection. The overcurrent relay is set to prevent operation on the maximum voltage expected across the Thyrite for an external fault.

The application of the high impedance differential relay is based on all of the CT's being set to the same ratio. In some installations there may be CT's of different ratios but with ratio matching taps available to select ratios that match. This could lead to problems in this application because of voltage magnification that results as shown in Figure 7. Depending on the disparity in ratios, the application shown in Figure 7 may be acceptable provided the voltage developed across the full winding of the tapped CT does not exceed the rating of the CT, terminal blocks, etc. It may be possible to use auxiliary CT's to obtain correct ratio matching but the CT's must have the ability to deliver the voltage necessary to produce operation for internal faults. These techniques and other possible solutions are described in detail in reference 2.

It is generally not advisable to connect other devices in the CT circuits used in a high impedance differential scheme because the added burden may increase the tendency for CT saturation or result in a setting that is beyond the range of the high impedance relay.

One advantage to using this type of relay is that the junction point of all of the CT's can be (and should be) made in the yard, rather than in the station house. Location of the junction point in the yard minimizes the amount of wiring required and in turn leads to lower settings and thus more sensitive protection.

Linear Couplers

Linear couplers, which have no iron in their core, can be used to overcome the problems caused by CT saturation. These devices have a linear characteristic that produces a voltage in the secondary that is directly proportional to the primary current. A typical application is shown in Figure 8. For an external fault, the sum of the voltages will be equal to zero (or very nearly so).

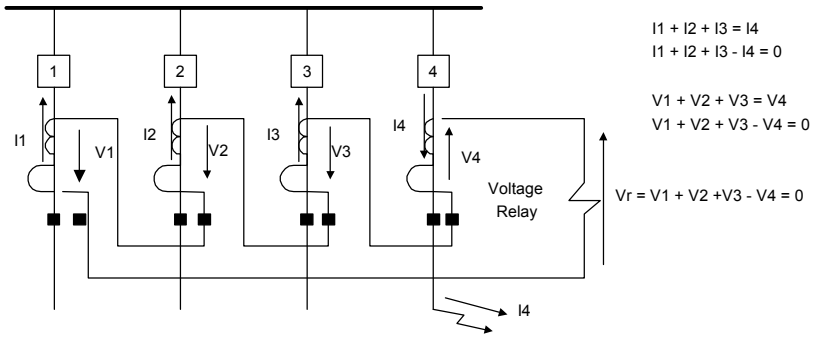


Figure 8 - Linear Couplers

On the other hand, the voltages all add together for an internal fault, thus producing sufficient voltage to operate the relay.

These devices provide a rather simple solution for bus protection, and some applications are in existence, but linear couplers have not been widely accepted because of their special characteristics and limited application.

Percentage Restrained Differential Relay

A percentage restrained differential relay takes cognizance of the fact that there may be

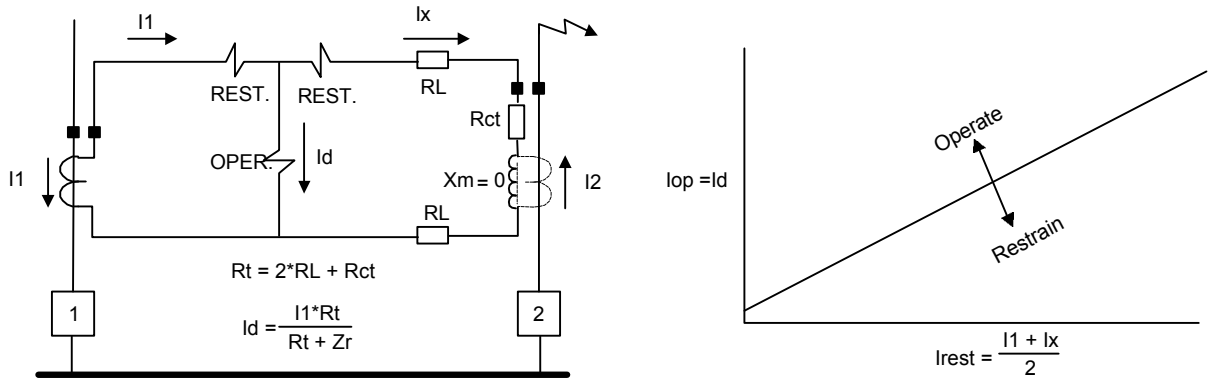


Figure 9 - Simple Percentage Restrained Differential Relay

error current in the differential circuit . A simple percentage restrained relay is shown in Figure 9. One method of obtaining restraint current is defined in the Figure. The relay will operate when the differential current (Id) is greater than some percentage of the total restraint current. The amount of restraint is generally adjustable. The characteristic of the relay is such that as the restraint becomes larger, so does the operate or difference current required to produce an output.. This type of operation produces the characteristic shown to the right in Figure 9. The slope of the characteristic is dependent on the percentage restraint setting.

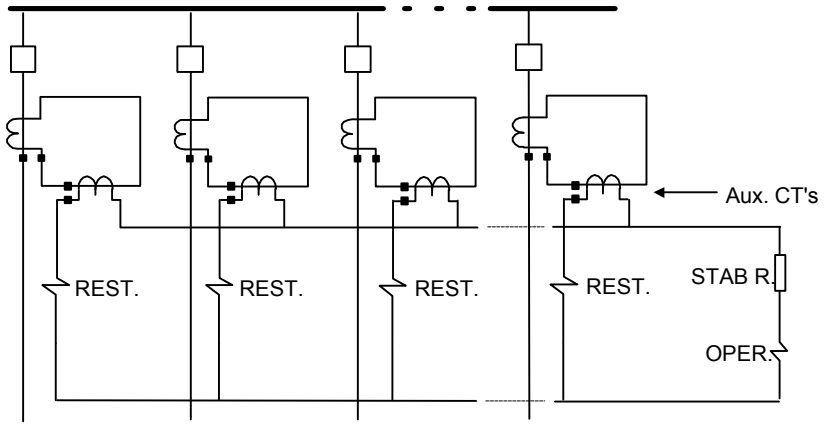


Figure 10 - Percentage Restrained Differential Relay with Auxiliary CT's

The auxiliary CT's are selected to provide a common turns ratio. Selection of t he stabilizing resistor (STAB R.) is based on:

1. The sensitivity of the relay
2. The slope setting that is desired
3. The largest total resistance in the CT secondary circuits as measured from the main CT to the relay.

In other words, the stabilizing resistor is selected so that the operating current will not exceed a set value even in the event total saturation were to occur in the main CT circuit having the highest amount of resistance (worst case condition because higher resistance forces more current to flow through the operate circuit - see Figure 5).

This type of relay requires that all of the CT leads be brought in to the relay house for connection to the relay. The main CT's can also be used to operate other relays provided the added burden is not so large as to preclude selection of a suitable stabilizing resistor.

Low Impedance Current Differential

It was pointed out earlier that a low impedance current differential relay used for bus protection would need a very high setting or a significant amount of time delay to prevent misoperation because of CT saturation. It is possible to use a low impedance device if steps are taken to overcome the effects of CT saturation. Consider the situation shown in Figure 11.

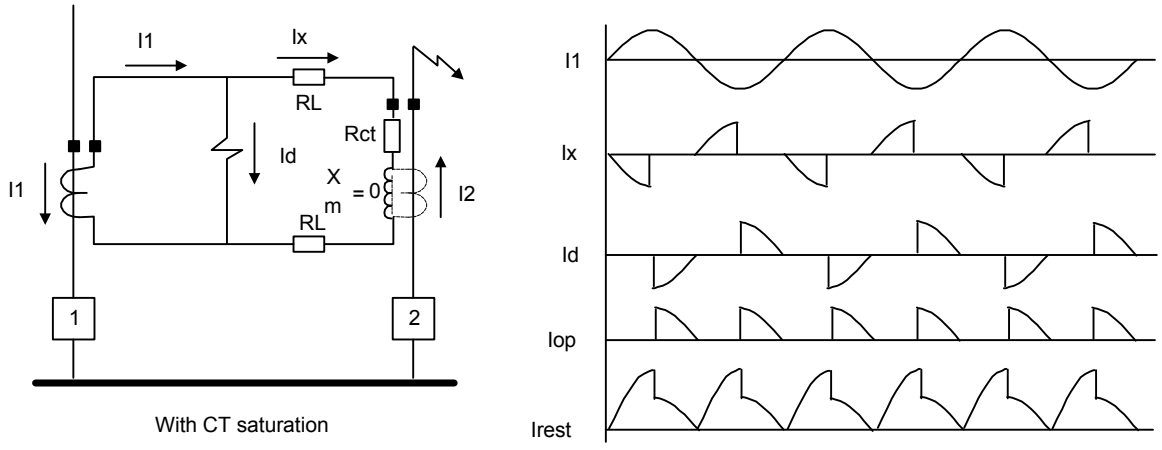


Figure 11 - Currents During Saturation

The currents are shown in oversimplified form and are meant for demonstration purposes only. The CT in Line 2 is assumed to saturate completely every half cycle so that the current Ix will be as shown. As a result of the collapse of the CT in Line 2, the differential current Id will flow. The operating current, Iop, is the absolute value of the differential current Id and the restraining current, Irest, is the sum of the absolute values of all of the currents entering and leaving the junction point of the CT circuits. The key point to note in this Figure is that the restraint current is significant during the period of non-saturation while the operating current at the same time is

equal to or very nearly equal to zero. The relay shown in Figure 12 takes advantage of this condition to prevent operation during external faults with significant saturation in the fault CT, but to allow operation during internal faults without any delay. High speed operation, in the order of 5 to 10 milliseconds, can be obtained for heavy faults. The current differential element shown in Figure 12 is in effect a percentage restrained overcurrent relay; i.e., the differential element will produce an output when the operating current (Iop) exceeds Kr percent of the restraining current (Irest). The wave shape element, produces an output to block tripping when the restraining current is greater than Ks percent of the operating current. As noted earlier, the restraining current will be significantly larger than the operating current during the period of non-saturation so that blocking will be initiated at that time. The timer shown in the wave shape element has a twenty (20) millisecond dropout so that the blocking signal will be sustained even during the period of saturation when the operating current will exceed the restraining current. The wave shape element cannot operate unless the starting elements first operate. The starting elements operate on the change in restraining current and/or a drop in voltage if a source of voltage is available from the bus and is brought into the relay.

This relay also requires that all of the CT leads be brought into the relay house for connection to the relay.

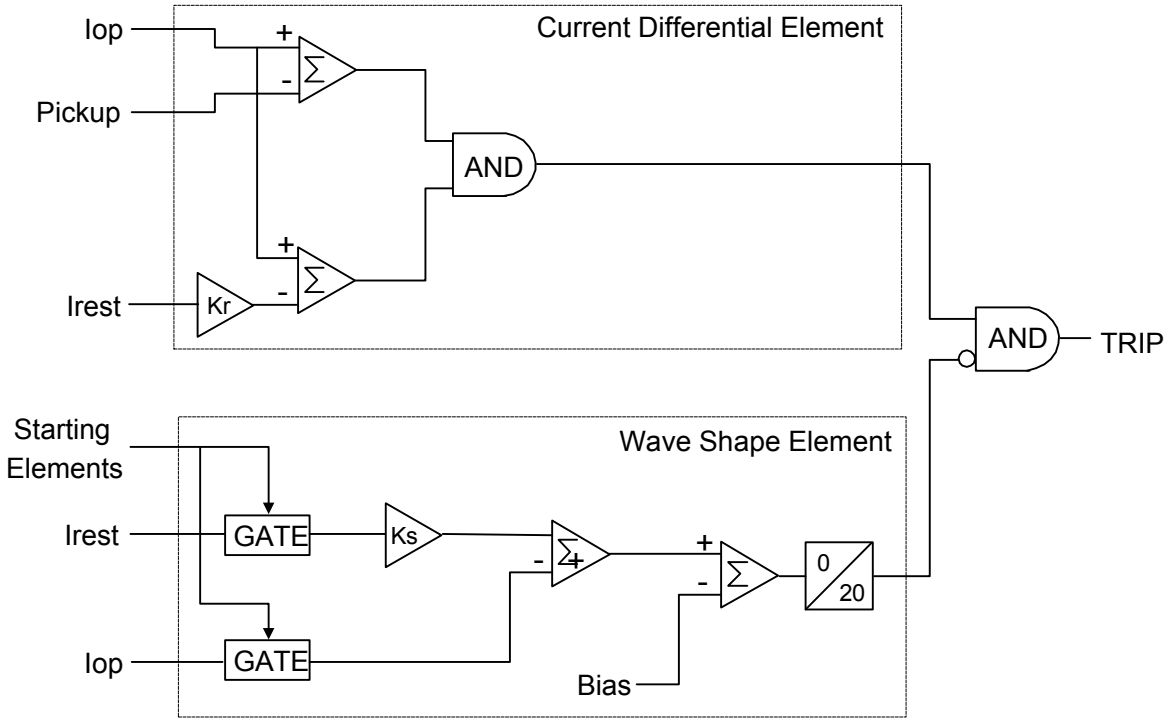


Figure 12 - Low Impedance Current Differential with CT Saturation Detection

The relay shown in Figure 12 can be implemented with analog circuitry or digital circuitry. Digital circuitry has the following advantages:

- Self-checking to provide increased security and dependability
- Selection of the circuits connected to the bus to be protected (in multi-bus applications) can be done via software rather than through external switching of the CT circuits.

Bus Arrangements

In some bus arrangements, it is common to switch lines to different buses in the substation to facilitate operation and/or maintenance. A simple main and transfer bus arrangement is shown in Figure 13. In this arrangement, the tie breaker (TB) is connected to one of the lines through the transfer bus while the regular line breaker is removed from service. The switching of the breakers is accomplished via the line switches (LS--) associated with the breaker to be switched. In the low impedance differential relay described above, auxiliary switches (a and b) associated with the line switches (and certain breakers in some arrangements) are brought into the relay and the state of these switches is used by the relay to determine which breakers are connected to which bus so that the correct differential zones can be established. The CT's in this situation are always connected to the relay, thus CT switching is not required, because the determination of the zone of protection is done via software in the relay. Separate trip outputs are provided for each breaker thus only those breakers associated with the faulted bus will be tripped at the time of a bus fault (one relay can protect multiple buses).

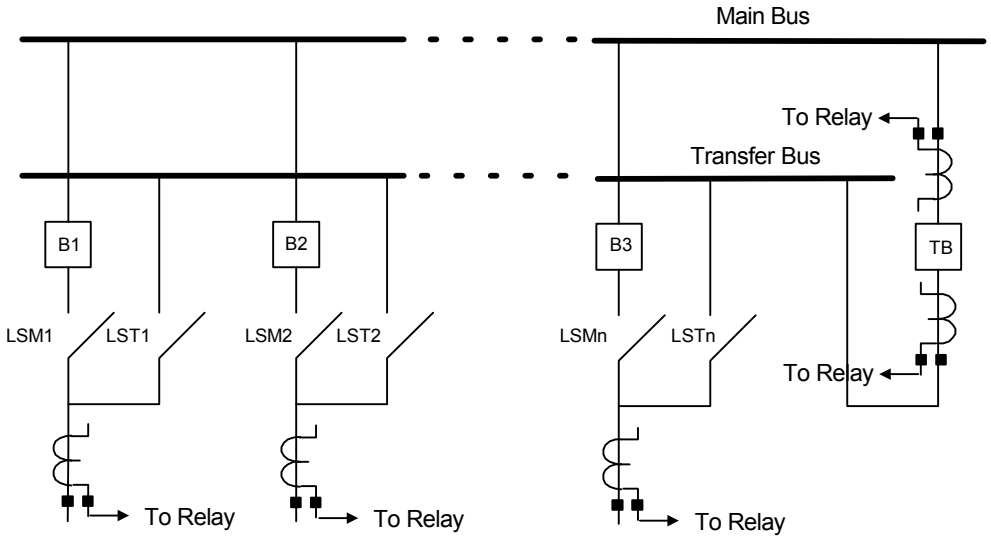


Figure 13 - Main and Transfer Bus Arrangement

All of the common bus arrangements plus more complex arrangements can be handled in addition to the simple main and transfer bus shown above. A much more complex arrangement is shown in Figure 14.

A novel bus configuration program is used with this relay to allow the user to input their specific bus arrangement. The program then generates wiring diagrams along with specific instructions to allow the relay to be built. The relay contains all of the necessary auxiliary CT's to allow ratio matching in the event that different ratio CT's are involved in the application.

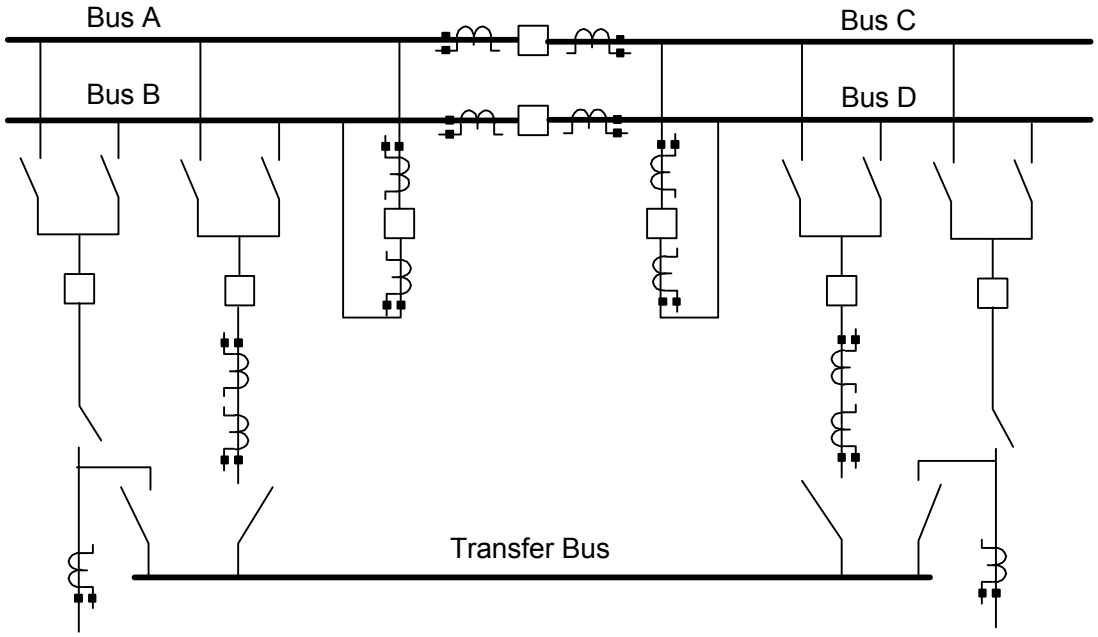


Figure 14 - Double Bus with Transfer Bus

Some of the advantages of using digital technology were noted earlier. Other advantages, as noted below, are also obtained:

- Ability to obtain oscillographic data for faults
- Metering capability
- Individual settings for current detection in each feeder
- CT supervision (secondary open)
- Line switch pole disagreement (alarm)
- Breaker failure protection can be included for each breaker

Conclusions

High impedance relays have been used to provide effective, low cost bus protection for many years, but have limitations in complex bus arrangements and in arrangements involving multi-ratio CT's. Traditional low impedance current differential relays generally can not be used because of the problems associated with CT saturation. A digitally implemented, low impedance differential relay, with the wave detection element described earlier, overcomes the effects of CT saturation.. Additional benefits are also gained through the use of digital technology.

References

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2. Application of PVD Relays Using Different Ratio Current Transformers, GE publication GET-6455

3. IEEE C37.97-1979 (Reaff 1990) Guide for Protective Relay Applications to Power System Buses

4. The Art and Science of Protective Relaying, C. Russell Mason

5. Protective Relaying, Principles and Applications, J. Lewis Blackburn

Appendix A

Partial Differential Protection

Partial differential protection is commonly used on distribution buses and is often discussed in the literature. It is included in this Appendix for the sake of completeness.

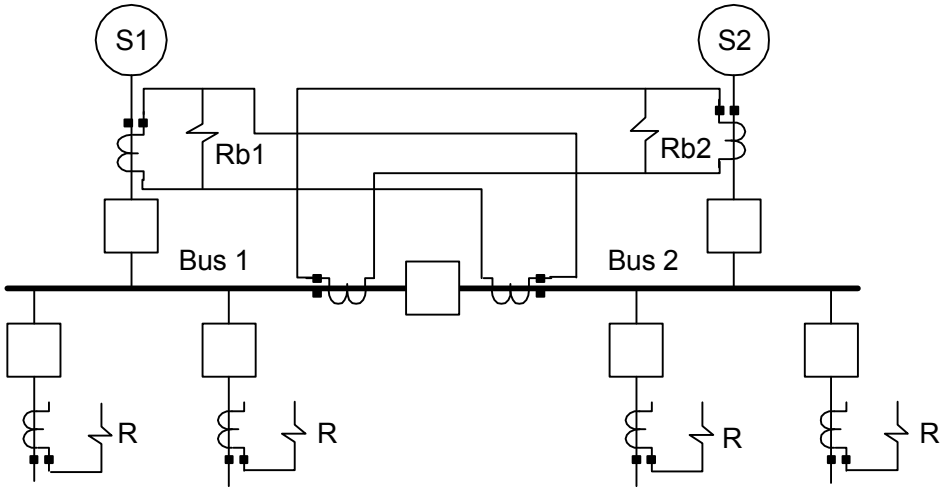

Figure A1 - Partial Differential Relaying

Simple overcurrent relays (time and instantaneous) are most often used in these applications. The partial differential relays, Rb1 and Rb2, operate for respective bus faults, but must be set to coordinate with the downstream devices

Directional Comparison Bus Protection

Another type of protection that is available but not extensively used is bus protection by directional comparison as shown in Figure A2.

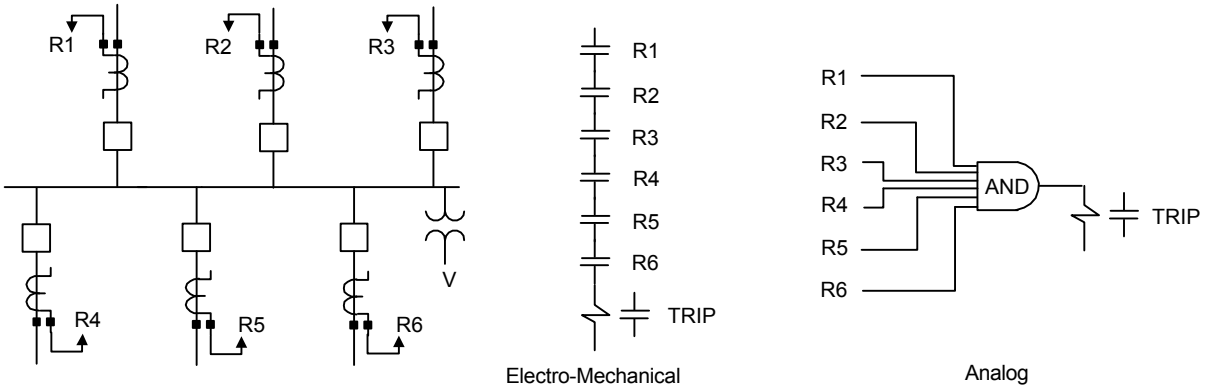

Figure A2 - Directional Comparison Bus Protection

This type of protection requires a directional function (overcurrent or distance) on each of the lines with each function connected so that each is looking into the bus. A trip output is produced when all of the directional functions operate which will only be the case for a bus fault. Electro-mechanical implementation of the scheme requires all of the contacts to be connected in series which in effect forms an AND function which is the means used to implement the analog version of the system. This system can be applied with current transformers of different ratio, but does require a source of potential in order to provide the directional action of the functions.